

THE EVOLUTION OF A HOLOCENE FRINGING REEF AND ISLAND:
REEFAL ENVIRONMENTAL SEQUENCE AND SEA LEVEL CHANGE
IN TONAKI ISLAND, THE CENTRAL RYUKYUS

BY

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ABSTRACT

Within the Indo-Pacific region Holocene reef development over the last 6000 yBP has occurred during a near stable sea level period. In particular, development of reef flat and related features have been associated with the stillstand. This is illustrated by the Holocene evolution of a reef in the Japanese Ryukyu Islands. A continuous reef structure, 8 m in thickness and 630 m in length, was observed from a fresh excavation in a modern fringing reef in the western part of Tonaki Island of the central Ryukyu Islands. Documented by 34 radiocarbon ages, the reef first reached a relative sea level of ca. 1 m above the present level at about 5200 yBP by growth of branching *Acropora* thickets, and by accumulation of angular clasts of tabular *Acropora* at the landward side. Storm features occur within all the observed reef structure and suggest that the reef has been continuously affected by high-energy events for at least 5500 yBP. The topographic outline of the modern fringing reef was formed at an early stage of sea level stillstands affected by wind, climate, and substrate topography. Delayed closure of the 'Holocene high energy window' resulted in vigorous reef growth on the landward side. The reef flat accreted seaward about 400 m during the last 4500 yBP with the development of spurs and grooves. The growth environment shifted from a sheltered to a wave-affected condition during the seaward accretion of the reef flat. Reduced colony sizes of tabular *Acropora* and decreased upward reef growth rates also occurred at about this time. With the seaward accretion, the shoreward grooves became isolated and infilled by rounded clasts. Radiocarbon age from an early archeological feature (Touma and Oshiro 1979) indicates that the formation of a Holocene tombolo is closely tied to sea level fall around 3500 yBP. This sea level fall and sufficient development of wave resistant structures at the reef edge, provided shore protection and contributed to tombolo stability.

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INTRODUCTION

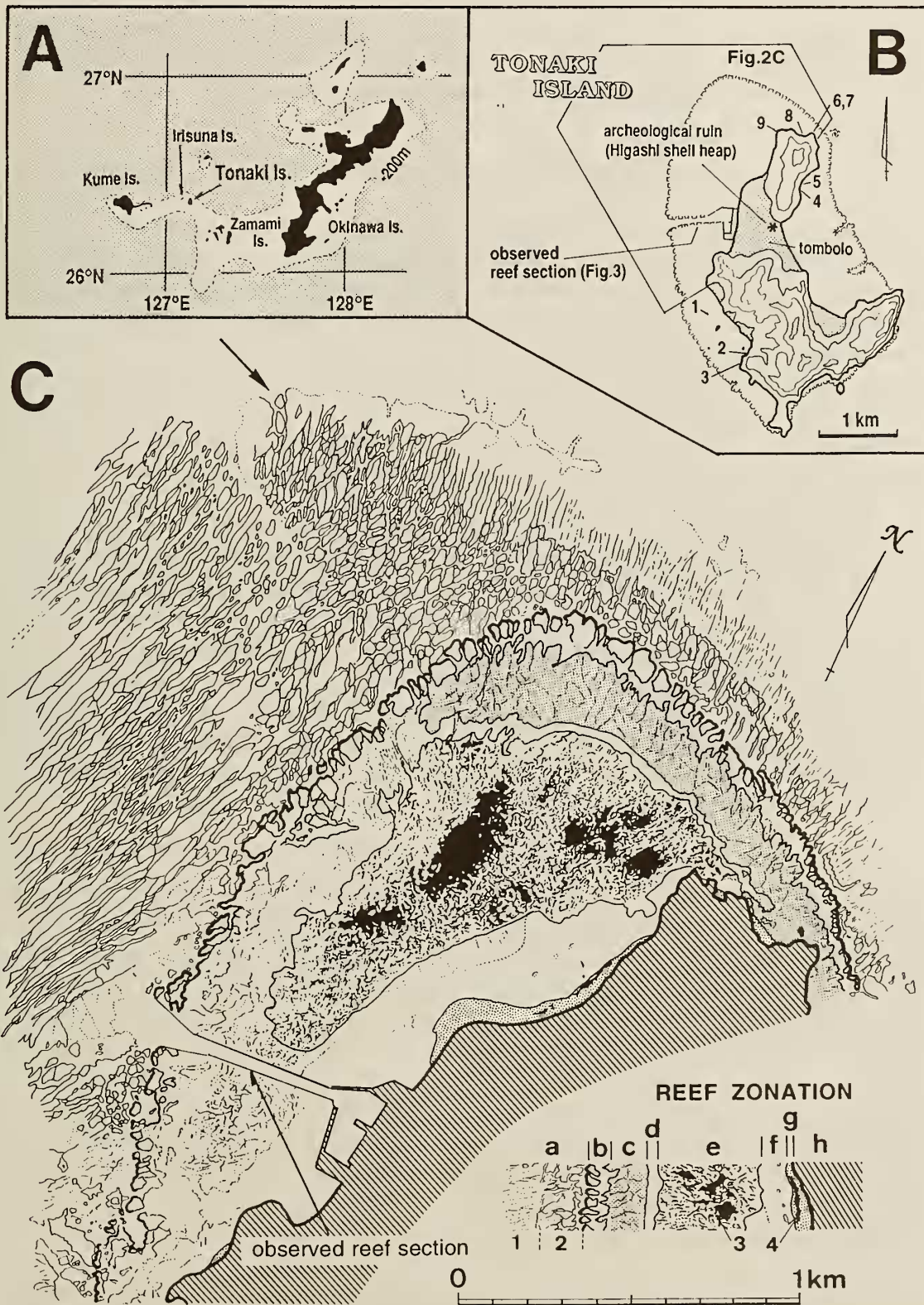
As coral reefs grow they can alter their own environment. In mid-Holocene times, reefs that were still catching up with sea level had minimal wave baffling effects. Neumann (1972) named this the 'Holocene high energy window'. Subsequent reef growth produces a protective crest which in turn results in the development of the back-reef area. On fringing reefs, in particular, this may result in a shallow lagoon or moat with ponding of terrestrial run-off which may limit coral growth (Ginsburg and Shinn 1964; Schlager 1981; Neumann and Macintyre 1985; Acevedo *et al.* 1989).

Sea level stillstands of the order of millennia can produce substantial fringing-reef flats (Buddemeier and Hopley 1988). In the Indo-Pacific region where a Holocene stillstand has occurred for approximately the last 6000 years, understanding of reef growth in response to both early Holocene sea level rise and late Holocene stillstand is needed to fully understand reef evolution.

This study reports on the evolution of the modern fringing reef and sea level change in Tonaki Island, the central Ryukyus (Fig. 1), as deduced from a continuous reef section in a harbor excavation across western Tonaki Reef. Supporting evidence also comes from coastal landforms including a fossil reef surface overlain and protected by beach conglomerate, marine notches, and a tombolo (Fig. 2). Tonaki Island is a high island with two small hills consisting of late Paleozoic and Cenozoic formations (Konishi 1964) joined by a tombolo (Fig. 2B). The tombolo is 330 to 740 m wide and 330 to 1000 m long. Some of the features of the tombolo developed on Tonaki Island are similar to the cay islands of the Great Barrier Reef (Gourlay 1988), Solomon Islands and British Honduras (Stoddart 1969).

Hopley (1968; 1971; 1975) described development of island spits on continental high islands of North Queensland and concluded that the many similarities between the fringing reefs and associated deposits of the high islands and the low wooded islands (complex reef islands) implied a comparable Holocene history (Hopley 1982, p371). Reef structure and radiocarbon dates observed from the western Tonaki trench and coastal features has enabled us to discuss the time-series relationship between reef environmental change, sea level change, and subaerial deposit formation by reference to

Figure 2. (A) Location; (B) general topography of Tonaki Island. The *contour lines* are drawn at 50 m intervals for land topography. *Numericals* in B indicates sampling sites of dated corals and beach conglomerate shown in Table 2. Location of observed reef section is indicated in B and C. (C) Modern reef topography of the northwestern Tonaki Reef. *Bold arrow* shows submarine ridge extending to the northwestern small rocky island (Irisuna Island). Reef zonation: *a* reef slope (*1* furrowed platform, *2* with spurs and grooves), *b* spur and groove zone of reef edge, *c* reef crest, *d* inner part of reef crest (some area recognized as a rubble flat), *e* shallow lagoon (*3* coral alignment), *f* inner reef flat, *g* beach (*4* beach rock), *h* land.



these observations and radiocarbon dates of a fossil reef surface and the earliest archeological ruin on the tombolo of Tonaki Island as described by Touma and Oshiro (1979). This relationship between the reef and associated Holocene landforms indicates how reefs respond to external and internal environmental change.

MATERIALS AND METHODS

In the Ryukyu Islands, many trenches have been excavated to construct harbors and associated ship channels across modern fringing reefs. Such excavations provide the opportunity to observe the continuous structure of modern reefs. Reef structure directly observed from trench walls reveals the exact location of sedimentary facies, shape and size of coral colonies and coral clasts in contrast to observations made from reef cores (Kan and Hori 1991). In Tonaki Island, a harbor excavation reaching 8 m in thickness and 630 m in length across the western Tonaki Reef, provides a continuous reef section (Fig. 2). The southern wall of the excavation provided a fresh reef section because the survey was carried out immediately after widening of the trench in 1989.

The reef profile (Fig. 3) was surveyed using measuring tapes, a 5-meter pole and depth meter to define micro-topographic features and to provide the basis for later descriptions of the section. Descriptions of the reef structure were carried out from the reef surface to the foot of the excavation at approximately 5 to 10 m intervals along the entire length of the section. The survey was carried out at closely spaced horizontal intervals especially at the boundaries of the sedimentary facies. Fossil corals were collected from the excavation by using a hammer and chisel. Twenty-five radiocarbon ages were obtained for corals in this reef section (Table 1). These dates were established by methanol liquid scintillation counting, at the Dept. of Geography, Hiroshima University. Laboratory procedures were based on Fujiwara and Nakata (1984).

The geomorphological map of the northwestern Tonaki Reef (Fig. 2C) was prepared to document the zonal and the micro-topographic features. The reef topography is based on the interpretation of field observations in 1989 and the 1977 color aerial photographs scaled to 1:10,000. Coastal landforms such as fossil reef surface overlain by beach conglomerate, and marine notches were investigated to document mid-to late-Holocene sea level indicators in 1991 and 1996 (Fig. 2). The altitude data were revised with reference to tide tables. Tidal values in Tonaki Island are corrected by reference to those in Zamami Island, near Tonaki (Fig. 2). Mean high (low) water level in Tonaki is about 0.6 m above (below) mean sea level (MSL) which is 1.16 m above the tidal datum. Tidal range is approximately 2.0 m at spring tide. Nine radiocarbon ages were obtained from *in situ* corals in the modern reef surface and in the fossil reef surface overlain by the beach conglomerate (Table 2). These ages were dated by Prof. emeritus K. Kigoshi of Gakushuin University.

X-ray diffraction was used to confirm the absence of calcite in all dated samples. Age calculations are based on the Libby half-life of 5568 ± 30 years. Errors are indicated at the range of $\pm 1 \sigma$. The dates have not been corrected for isotopic fluctuations or

environmental factors because we have no data on the ocean ^{14}C reservoir effect for the Ryukyu Islands.

RESULTS

Topography of western Tonaki Reef

On Tonaki Reef, a reef crest has developed in the north where topographic zonation is clearly defined, and flat topography with poor zonation occurs on the western reef (Fig. 2C). On the northern part of the reef, spurs and grooves on the reef edge and furrows on the submerged platform off the reef edge, at a depth between 10 to 15 m align with the prevailing northerly wind of winter seasons. These features are similar to the northern reef of Kume Island described by Takahashi and Koba (1977) and Kan (1990), which lies 30 km west of Tonaki Island. The distribution pattern of reef slope coral ridges changes abruptly on the northwestern reef slope where a submarine ridge extends westward (bold arrow in Fig. 2C). The long axes of the coral ridges and honeycombed furrows suggest that a southwesterly current dominates on the western reef slope. The observed reef section bisects a large number of spurs and grooves (Fig. 3), because the orientation of spurs and grooves is oblique to the reef edge on the western reef (Fig. 2C).

The dominant coral assemblage of the reef edge is tabular or encrusting *Acropora*. On the northern reef, a coral rubble flat of tabular *Acropora* clasts has developed behind the reef crest. In the shallow lagoon, branching *Porites* dominate in the northern part. However, the lagoon tends to shallow towards the south where sea grass beds, with branching *Montipora* and *Pavona cactus*, are found.

Internal structure beneath the reef flat

Four major bio-lithofacies are identified for the upper 8 m of reef structure in the western Tonaki reef flat. Three distinct zonal structures were observed: from seaward, tabular *Acropora* framework facies; tabular *Acropora* transported rubble facies; tabular *Acropora* reworked facies; and branching *Acropora* facies. These facies are arranged vertically in the reef structure (Fig. 3). The other lithofacies described below are subordinate.

1) Tabular *Acropora* framework facies: *In situ* growth and accretion of tabular or plate *Acropora* dominates the outer half of the reef structure. This facies constitutes a large part of the convex topography of spurs or paleo-spurs (Fig. 3) and abut thick beds of tabular *Acropora* transported rubble facies described below (Fig. 4B). While large size *in situ* tabular *Acropora* colonies, around 2 m in horizontal dimension, are dominant on the inward end of this facies zone (Fig. 4A: 340 m point in Fig. 3), colony size decreases to 20 to 50 cm at the outer edge. Coincidentally, the upward reef growth rate gradually decreases seaward (Table 1) as follows: 8.2 m/ky (between TN-12 and 13) for the earlier spur dated around 4500 yBP; 4.1 m/ky around 4000 yBP (between TN-6 and 7); 3.6

m/ky (between TN-4 and 5); 3.2 m/ky (between TN-2 and 3); 1.2 m/ky (between TN-1 and present).

2) Tabular *Acropora* reworked facies: The unconsolidated platy clasts of tabular *Acropora* have accumulated (Fig. 4C) to at least 6m thickness and formed a sedimentary zone behind the tabular *Acropora* framework facies (Fig. 3). These *Acropora* clasts (Fig. 4D) are relatively well preserved and essentially overturned *in situ* colonies. The radiocarbon ages between TN-20 and TN-21 are reversed, despite 2.6 m difference in their depths (Table 1).

3) Tabular *Acropora* transported rubble facies : In the outer half of the reef structure, rounded coral clasts (Fig. 4E) have densely infilled the *in situ* tabular *Acropora* facies (Fig. 3). Some clasts are coated by calcareous algae (in the form of rhodoliths; Fig. 4F), which suggests that they had been tumbled. These are similar to those that have accumulated in the present-day grooves of the reef edge. Radiocarbon ages of rubble lag approximately 400 to 900 years behind neighboring *in situ* tabular *Acropora* facies (between TN-9, 12 and 10; Fig. 3).

4) Branching *Acropora* framework facies: Thickets of *in situ* branching *Acropora* (Fig. 4G) form a framework zone which exceeds 100 m in width and is more than 6 m thick (Fig. 3). These colonies were relatively intact (Fig. 4H). However, calcareous algae which covered the surface of branches makes species identification difficult. Radiocarbon ages (Table 1) show this coral thicket had been growing for over 400 years. The observed upward reef growth rates were 6.3 m/ky (between TN-14 and 15) for this thicket. Aside from the fine sediment that covers the excavation (Fig. 4G), little sediment was observed infilling the branching framework.

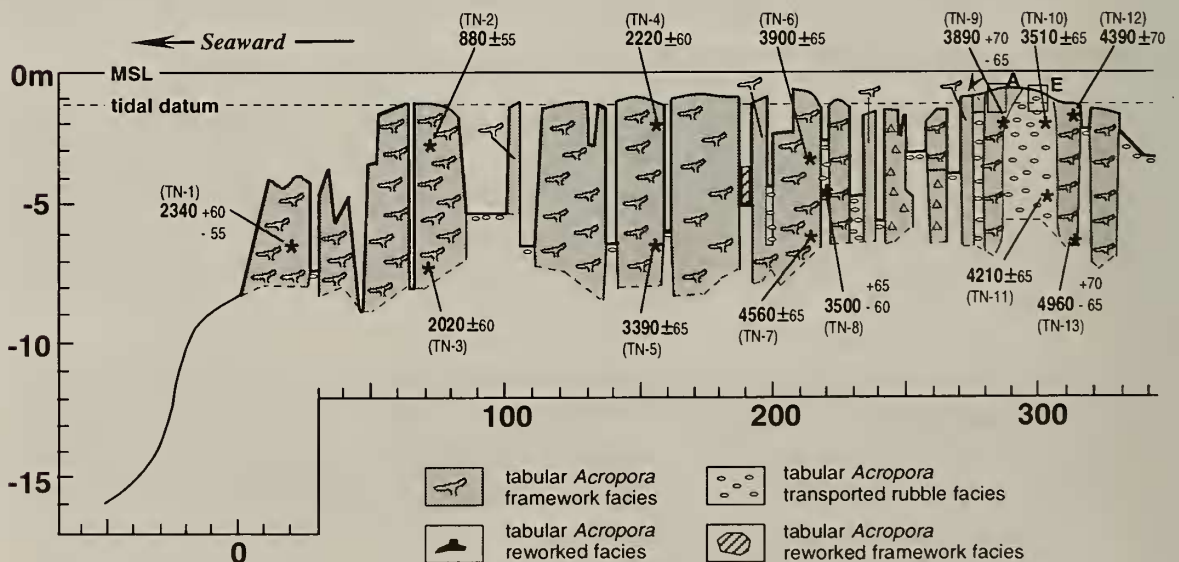


Figure 3. Reef structure and radiocarbon ages of fossil corals in the western Tonaki Reef. Lettered squares indicate positions of photographic sites presented in Fig. 4.

5) Tabular *Acropora* reworked framework facies: Tabular corals and calcareous algae constitute blocks 1 to 5 m in diameter. This bio-lithofacies is similar to the tabular *Acropora* framework facies of the reef margin. However, directions of individual coral growth and of accumulated coral colonies are different from the framework facies.

6) Mixed coral framework facies: This facies constitutes corals, calcareous algae and skeletal grains. No dominant coral genus was observed in this facies.

Beside these bio-lithofacies, the following *in situ* coral colonies larger than 2 m in diameter are identified in the growth fabric: foliaceous *Heliopora*, stubby branching *Acropora*, and hemispherical *Lobophyllia*. No terrigenous facies or Pleistocene limestone was observed within the section.

Late-Holocene sea level change

On Tonaki Island, part of the Holocene reef flat is surmounted by undercut blocks (Konishi 1964). It has been suggested that the reef flat originally developed 80 cm higher than the present sometime in the late Holocene (Konishi *et al.* 1974). Beach conglomerate which overlies the landward end of the reef has also resulted in protection of the reef surface against erosion (Fig. 5). These features, together with marine notches cut into the Paleozoic limestone cliffs are considered to be sea level indicators (Kawana 1996). Nine radiocarbon ages for corals obtained from the modern and fossil reef surface (Table 2, Fig. 5) show that the sea level achieved a maximum ca. 0.9 to 1.3 m higher than present ca. 5200 yBP. This mid-Holocene maximum level extended until around 3650 yBP, with a relatively sharp fall taking place at that time (Fig. 6).

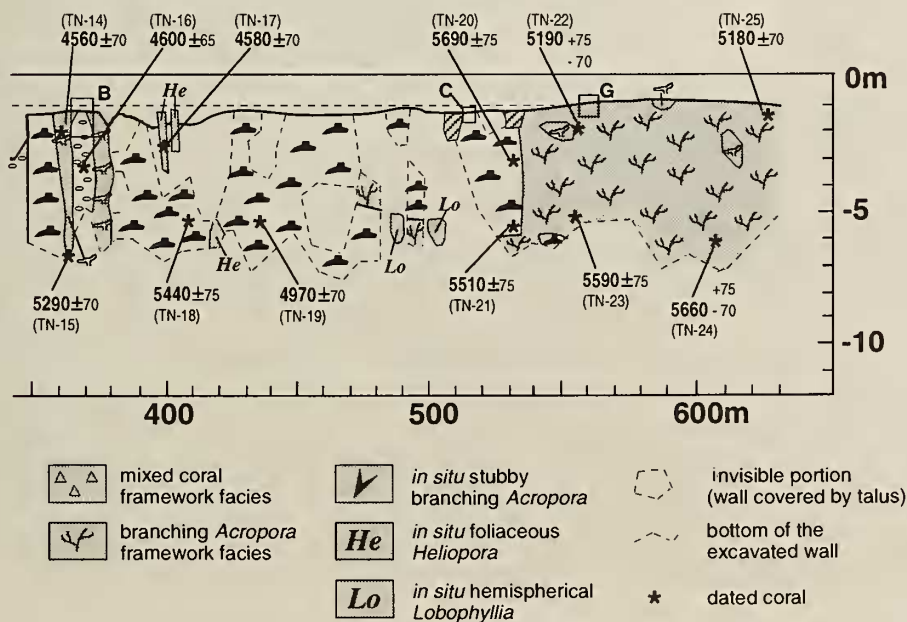


Table 1 Radiocarbon ages from Tonaki Reef excavation.

Sample No.	Site (m) *	Depth (m) below MSL	Material		Labo. No.	Radiocarbon Age (yB.P. $\pm 1\sigma$) T(1/2)=5568yrs	Upward Growth Rate (m/kyr)
			Genus	Life Form			
TN-1	18	6.5	<i>Platygyra</i>	hemispherical †	HR-561	2340 + 60 - 55	1.2 ††
TN-2	70	2.7	<i>Acropora</i>	tabular †	HR-562	880 \pm 55	3.2
TN-3	70	6.4	<i>Acropora</i>	tabular †	HR-563	2020 \pm 60	
TN-4	153	2.1	<i>Acropora</i>	tabular †	HR-564	2220 \pm 60	
TN-5	153	6.3	<i>Acropora</i>	tabular †	HR-565	3390 \pm 65	3.6
TN-6	214	3.4	<i>Acropora</i>	tabular †	HR-539	3900 \pm 65	
TN-7	214	6.1	<i>Acropora</i>	tabular †	HR-540	4560 \pm 65	4.1
TN-8	220	4.6	<i>Acropora</i>	tabular ✱	HR-538	3500 + 65 - 60	
TN-9	280	2.1	<i>Acropora</i>	tabular †	HR-560	3890 + 70 - 65	8.2
TN-10	295	2.1	<i>Acropora</i>	tabular ✱	HR-534	3510 \pm 65	
TN-11	295	4.7	<i>Acropora</i>	tabular ✱	HR-535	4210 \pm 65	6.3
TN-12	305	1.8	<i>Acropora</i>	tabular †	HR-536	4390 \pm 70	
TN-13	305	6.5	<i>Acropora</i>	tabular †	HR-537	4960 + 70 - 65	
TN-14	357	2.4	<i>Acropora</i>	tabular †	HR-531	4560 \pm 70	6.3
TN-15	357	7.0	<i>Acropora</i>	tabular †	HR-532	5290 \pm 70	
TN-16	365	3.7	<i>Acropora</i>	tabular ✱	HR-533	4600 \pm 65	8.3
TN-17	395	2.2	<i>Heliopora</i>	foliaceous †	HR-559	4580 \pm 70	
TN-18	405	5.4	<i>Acropora</i>	tabular	HR-557	5440 \pm 75	8.3
TN-19	434	5.5	<i>Acropora</i>	tabular	HR-558	4970 \pm 70	
TN-20	529	3.1	<i>Acropora</i>	tabular	HR-551	5690 \pm 75	8.3
TN-21	529	5.7	<i>Acropora</i>	tabular	HR-552	5510 \pm 75	
TN-22	555	2.1	<i>Acropora</i>	ramose †	HR-553	5190 + 75 - 70	8.3
TN-23	555	5.4	<i>Acropora</i>	ramose †	HR-554	5590 \pm 75	
TN-24	606	6.3	<i>Acropora</i>	ramose †	HT-555	5660 + 75 - 70	8.3
TN-25	625	1.6	<i>Acropora</i>	ramose †	HR-556	5180 \pm 70	

* Site shows the sampling location corresponding to the horizontal scale of the reef section (Fig. 2).

† *in situ* coral

✱ rounded clast accumulated in groove

†† Growth rate is calculated on the basis of the TN-1 sample and the top of the spur (present).

The present is assumed, as the spur has not reached sea-level.

Figure 4. Holocene reef structures and components observed from the excavated wall of the western Tonaki Reef. Sites of the photographs are shown in Fig. 3. (A) *In situ* tabular *Acropora* facies, (B) paleo-groove (*b*) infilled by rounded coral clasts. Paleo-spur (*a*) composed of *in situ* tabular *Acropora*. (C) angular clasts of tabular *Acropora* reworked facies. (D) close-up of angular clast of tabular *Acropora*. (E) rounded coral clasts of tabular *Acropora* transported rubble facies. (F) a section of a rounded coral clast showing encrustations by calcareous algae. (G) branching *Acropora* framework facies. (H) colony of *in situ* branching *Acropora*.

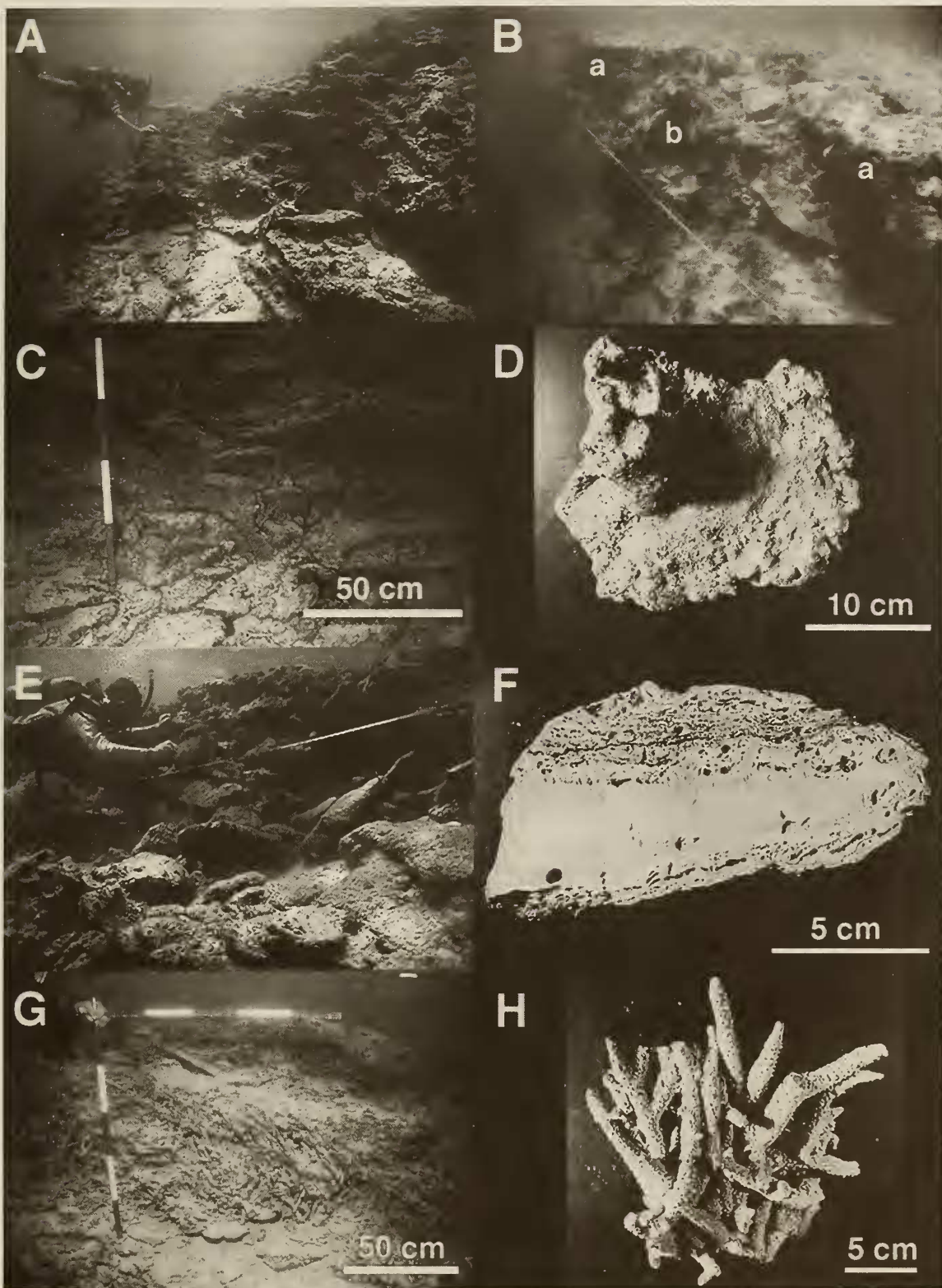


Table 2 Radiocarbon ages of *in situ* corals in coastal deposits in Tonaki Island (see also Fig. 5).

Loc. No. *	Radiocarbon Age (yB.P. $\pm 1\sigma$) T(1/2)=5568yrs	Material (Coral Genus)	Labo. No.	Explanation for Sampling Site	Elevation of specimen (m) above MSL
1	5150 \pm 100	<i>Porites</i>	GaK-15825	reef flat	- 0.6
2	4410 \pm 80	<i>Goniastrea</i>	GaK-15826	reef overlain by beach conglomerate	0.1
3	4790 \pm 140	<i>Goniastrea</i>	GaK-15827	reef in front of beach conglomerate	0.1
4	4430 \pm 110	<i>Porites</i>	GaK-15828	reef overlain by beach conglomerate	0.2
5	4980 \pm 90	<i>Goniastrea</i>	GaK-15829	do.	0.1
6	3640 \pm 190	<i>Porites</i>	GaK-15830	do.	0.7 †
7	4130 \pm 80	<i>Porites</i>	GaK-15831	do.	0.4 †
8	4820 \pm 130	<i>Goniastrea</i>	GaK-15832	inner edge of the reef flat	- 0.4
9	4890 \pm 100	<i>Porites</i>	GaK-15835	reef in front of beach conglomerate	0.2

* Location numbers are in Fig. 2B.

† The higher elevations of the specimens at Loc. 6 and Loc.7 are probably due to strong wave-affected coast.

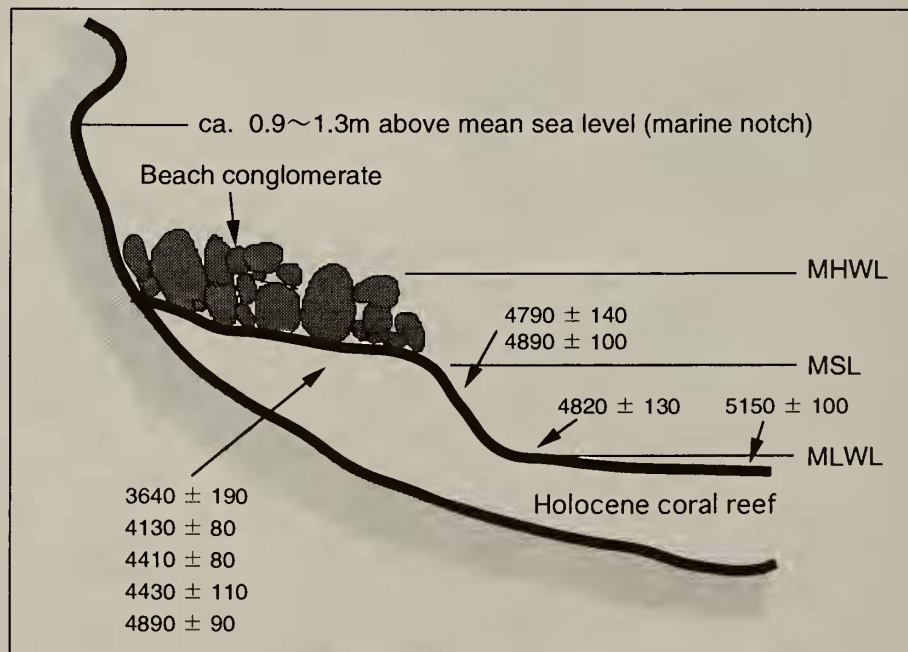


Figure 5. Schematic profile of Holocene reef, beach conglomerate and marine notch at the landward end of Tonaki Reef. Radiocarbon ages of corals indicate years BP (see also Table 2). MHWL: mean high water level, MLWL: mean low water level.

Reef growth and island formation

The western Tonaki Reef first reached the sea level at 5200 yBP by growth of branching *Acropora* on the landward side (Fig. 3). The accumulation of the reworked facies of angular clasts of tabular *Acropora* was around 5200 yBP. Around 4500 yBP, some spurs consisting of tabular *Acropora* framework reached sea level at the outer edge of the facies formed of tabular *Acropora* reworked (Fig. 3, TN-14). The transported tabular *Acropora* rubble facies gradually became thicker toward the inner reef flat (Fig. 3) where paleo-grooves have been entirely filled by rounded clasts (Fig. 4B). The reef flat of the western Tonaki Reef has accreted seaward about 400 m during the last 4500 yBP by the development of spurs and grooves. With the accretion of the reef margin, the landward grooves, which have become isolated from the sea, have been filled by rounded clasts.

The geomorphological evidence is supported by the history of human settlement in this area. Touma and Oshiro (1979) excavated the earliest archeological ruin located on the narrow part of the tombolo of Tonaki Island (Fig. 2B). Trench excavations show that bioclastic sand accumulated up to an elevation of 3.5 to 3.8 m. Above this sand,

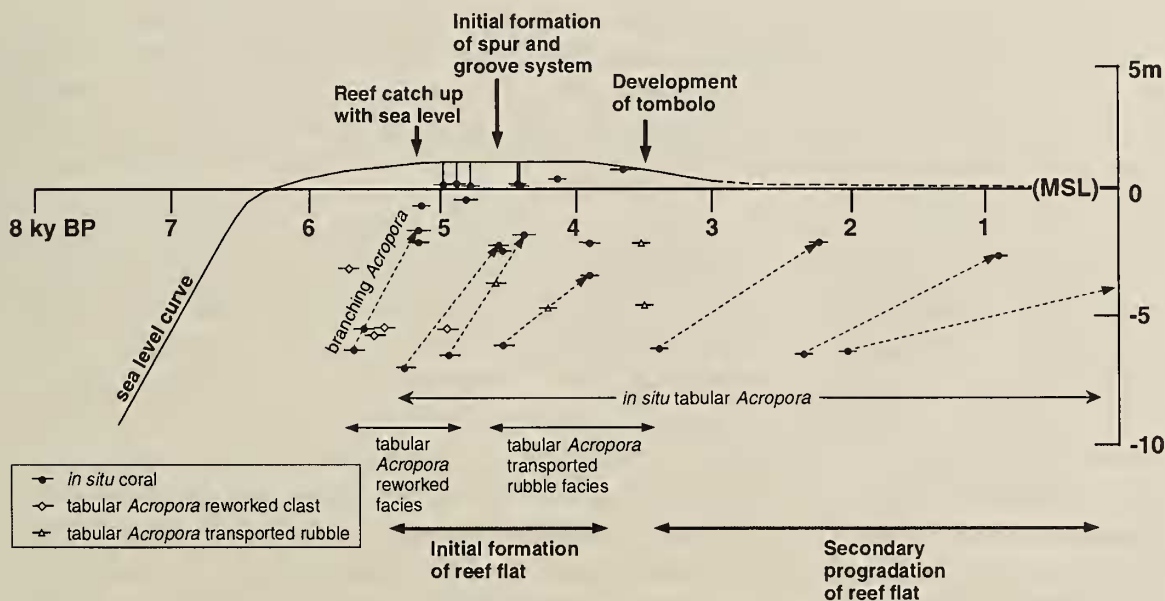


Figure 6. Sea level and reef growth in Tonaki Reef. The sea level curve (*solid curve*) until 5200 yBP is based on Kume Island, the neighboring island of Tonaki, when the 3 meters seismic uplift at around 2000 yBP (Koba *et al.* 1982) is subtracted from the curve of Kan *et al.* (1991). The *curve* after 5200 yBP is based on the coastal landforms and radiocarbon ages in Tonaki Island (see text). The *dashed lines* show the vertical reef growth at each site in Tonaki Reef (see also Fig. 3 and Table 1). A *horizontal bar* indicates the range of error in radiocarbon ages. A *vertical bar* indicates depth between the lowest low water level and the mean sea level for Tonaki Reef (0.9 m) to represent past sea level. The *vertical bar* is only for ages which are reliable sea level indicators.

two layers of brown humic sand were observed with a thickness of between 0.3 to 0.7 m below the present-day surface soil. The lower bed, just above the bioclastic sand, contains earthenware and shell middens. The radiocarbon age of shell material was 3510 ± 90 yBP (laboratory code: N-3080). This age coincides with the chronological determination of excavated earthenware (Touma and Oshiro 1979).

DISCUSSION

Storm features in the reef development

The Ryukyu Islands are located in the hurricane belt. Catastrophic storm events result in obvious degradation of coral colonies (see review of Rogers 1993) and produce large amount of coral clasts (e.g. MacNeil 1954; Hernández-Ávila *et al.* 1977; Scoffin 1993) during cyclic growth and destruction processes (Done 1992). The fragmentation of coral colonies appears to be a widespread and extremely important method of reproduction and distribution (Highsmith 1982). However, overturning of the colony is critical to survival (Chamberlain and Graus 1975). The morphology of tabular *Acropora* colonies which widen toward the top, when broken, produces the overturned accumulations of the tabular *Acropora* reworked facies. Storms on modern reefs can result in deposition in the back reef environment (c.f., MacNeil 1954; Newell and Bloom 1970) and mixing debris of varying ages (Johnson and Risk 1987). The observed age reversal between TN-20 and TN-21 in the tabular *Acropora* reworked facies is of similar magnitude to those obtained by Marshall and Davies (1982) from a drill core which penetrated into reef flat rubble facies in One Tree Reef on the Great Barrier Reef.

Catastrophic redistribution and abrasion by sediment have been observed during storm conditions (Kobluk and Lysenko 1992) especially along reef-edge grooves (Kan 1995). The unstabilized rubble is subjected to tumbling (Blanchon and Jones 1995) and infills cavities (Newell 1956; Edmunds and Witman 1991). The transported tabular *Acropora* rubble facies accumulated between the tabular *Acropora* framework facies (Fig. 4B) where 'room and pillar structures' (Tracey *et al.* 1948) had been formed. Storr (1964) showed that water flow over the tops of reefs is erratic and the rate of flow is generally low, whereas passageways (e.g., grooves, reef tunnels) permit high flow rates. The initial accumulation site of fragmentated colonies (i.e., back reef or reef edge grooves) may cause the differentiation between angular or rounded rubble. The observed reef structure shows that the accumulated coral clasts form rounded rubble (transported rubble facies) after the development of a spur and groove system (Fig. 6).

Storm events can also destroy reef edge spurs (Stoddart 1962) and throw them onto the reef flat (Ladd 1961; Newell and Bloom 1970; Bourrouilth-Le Jan and Talandier 1985). The buried blocks of tabular *Acropora* reworked framework facies, along with the accumulation of a large amount of *Acropora* clasts and the tightly interlaced branching colonies (as in Fig. 4H) which may also be formed during the regenerative growth process of fragments (Kawaguti 1937; Gilmore and Hall 1976), suggest that the reef has been continuously affected by high-energy events.

Windward-leeward contrast in the reef development

In the fringing reefs of the Ryukyu Islands, several studies have demonstrated that the original growth axis, where the reef first reached sea level, forms the present reef crest (Takahashi *et al.* 1988; Kan *et al.* 1991; Kan and Hori 1993; Yonekura *et al.* 1994). Results of drilling in a reef of northwestern Kume Island, located 30 km west of Tonaki Island, shows the northern reef reached sea level earlier because of shallow substrate and exposure to the prevailing northerly wind of winter seasons (Kan *et al.* 1991). A similar pattern of formative time lag was described by Hopley and Barnes (1985) for a fringing reef in the Great Barrier Reef. This pattern of growth helps to understand the planimetric development of the northwestern Tonaki Reef which has a similar geographical setting.

A submarine ridge extending on the northwestern reef slope of the Tonaki Reef (bold arrow in Fig. 2C) may have contributed to the development of the reef crest of the northern reef because reef development is closely tied to antecedent slope break (Hubbard 1988; Kan *et al.* 1995). The northern Tonaki Reef may well have initially reached sea level and acted as a breakwater against the prevailing winter northerly winds (Fig. 7A).

This allowed zonal growth of branching *Acropora* thickets which is usually found in sheltered environments (Geister 1977; Pichon 1978; Done 1983). However, branching coral assemblages in shallow lagoons change in response to burying by sandy sediment (Nakai 1982). Siltation and suspended sediments also reduce coral growth (e.g., Aller and Dodge 1974; Dodge *et al.* 1974; Loya 1976). Mayer (1918) examined *A. hebes* which is a synonym of *A. aspera* (Veron and Wallace 1984) and same or similar species to the branching *Acropora* of the western Tonaki section. It was shown to be sensitive to the smothering effects of silt. The vigorous growth of branching *Acropora* for over 400 years, with indications of little sediment influence, may be explained by the tidal current which may have been flowing between the two islands at about 5500 to 5200 yBP (arrows in Fig. 7A) before the tombolo joined them together.

The northern reef may also have provided the large amount of angular clasts of tabular *Acropora* to the reworked facies that accumulated around 5200 yBP, because the tabular *Acropora* assemblage had not formed in the western reef but is distributed abundantly down to a depth of 5 m at the reef edge and decreases in deeper water in the Ryukyu Islands (Takahashi *et al.* 1985). At the early stage of reef flat formation, development of leeward reefs is strongly affected by the windward reef formation.

Styles of reef accretion and formation of reef zonation

Framework accretion with higher accumulation rates is dominated by branching corals with a high proportion of voids (e.g., Davies and Hopley 1983; Davies *et al.* 1985; Hopley and Kinsey 1988) and is especially associated with monospecific coral thickets (Highsmith 1982). Detrital sedimentation by storm events also results in high reef accretion rates (Davies and Hopley 1983). In the western Tonaki Reef, the early

stages of reef were developed by these two bio-lithofacies within a short period around 5200 yBP. They may have also contributed to the sediments of the broad inner reef flat at the western part of Tonaki Reef quickly infilling any shallow lagoons.

The duration of the 'Holocene high energy window' has some regional variation (Hopley 1984). The development of spurs consisting of tabular *Acropora* framework around 4500 yBP (Fig. 3, TN-14) intimates that the 'high energy window' has been progressively closed since 4500 yBP. Subsequently, the area available for active carbonate production has been reduced to a zone at the reef edge (Stoddart *et al.* 1978) as reported in other present-day reefs (e.g., Gladfelter *et al.* 1978; Kinsey 1981).

Since the size of wave-swept organisms depends on wave exposure (Denny *et al.* 1985), the smaller colony sizes of *in situ* tabular *Acropora* on the outer reef flat suggest that the growth setting has changed to a wave-affected condition with the outward migration of the reef flat. The decline in vertical growth rates at the outward edge of the reef flat (Table 1, Fig. 6) has accompanied this change.

Contrary to reefs where the crest kept pace with sea level, the delayed closure of the 'Holocene high energy window' resulted in vigorous reef growth toward the island. Subsequently, however, the area of active reef growth has shifted progressively seaward with the development of reef edge spurs. This gradual process has contributed to the build up of flat topography with poor zonation.

Timing of island formation and sea level fall

The time-series relationship between reef island formation and reef development has been previously described (e.g., Stoddart 1969; Stoddart *et al.* 1978; Hopley 1982; Woodroffe 1992). The Great Barrier Reef cays formed after 6000 yBP, coincident with reef flat formation, but were essentially complete in shape and size by 3000 yBP (Stoddart *et al.* 1978). On Tonaki Island, the vigorous reef growth around 5000 yBP appears to have provided the shallow substrate to establish the tombolo between the two islands and provided enough land for human inhabitation by about 3500 yBP (Touma and Oshiro 1979; Fig. 7B).

The sea level fall sometime after 3650 yBP in Tonaki Island is quite similar to those in Kosrae Island in the eastern Carolines of Micronesia where a 1 m fall has taken place after 3700 yBP (Kawana *et al.* 1995), and in the Great Barrier Reef where the mid-Holocene maximum level may have extended until 3700 yBP (Beaman *et al.* 1994; Larcombe *et al.* 1995). Evidence for sea level fall around 3700 yBP appears prevalent in the western Pacific.

Stoddart and Steers (1977) suggested that reef islands were formed as a result of sea level fall (see also, Pirazzoli and Montaggioni 1986; Roy and Connell 1991). Schofield (1977a, 1977b) demonstrated how reef islands formed due to sea level fall and the supply of sediment from reefs. Sea level fall resulted in reduced wave force at the shore. The seaward accretion of the reef also contributed to wave attenuation because

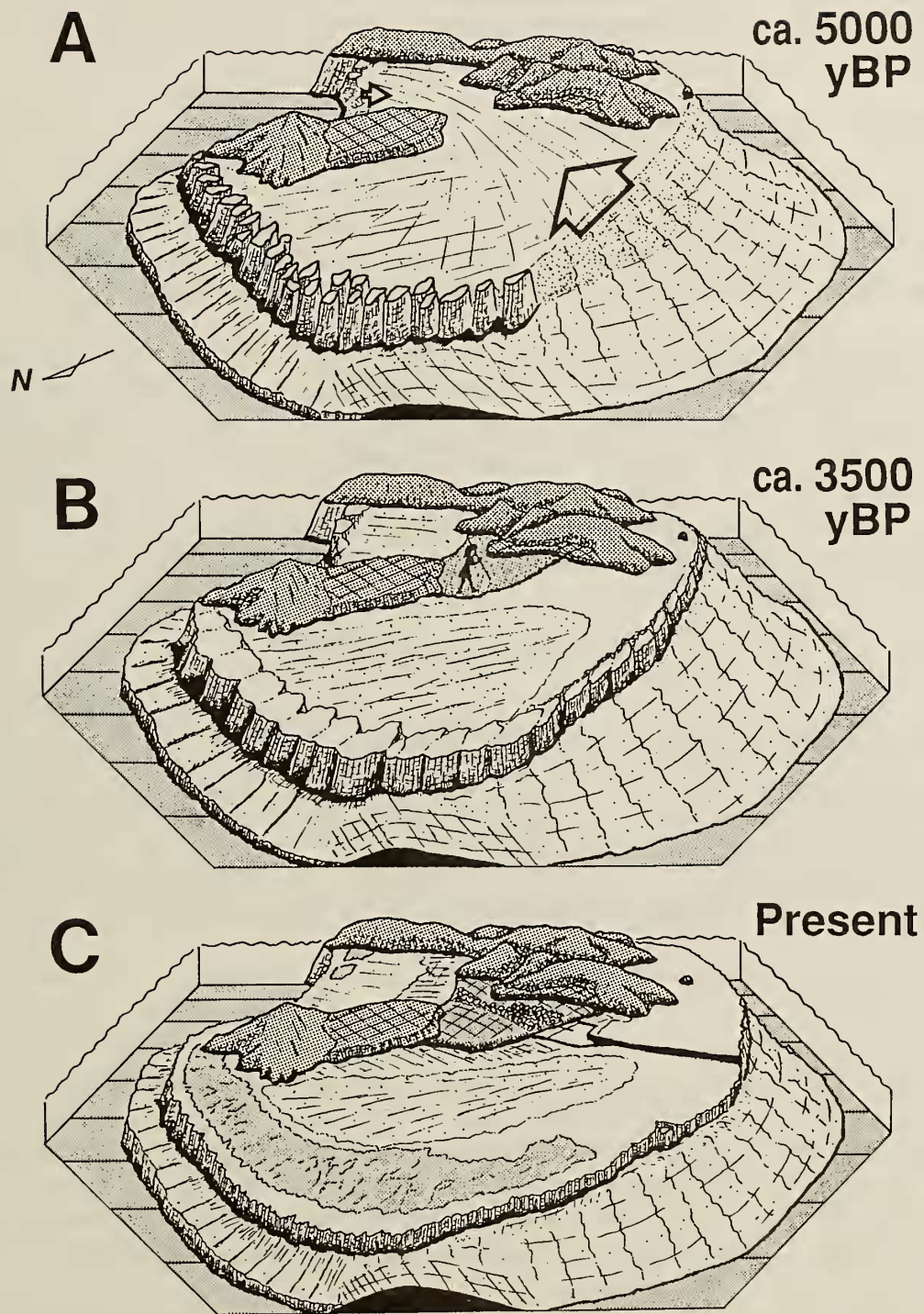


Figure 7. Schematic diagrams of the formation of the Tonaki Reef. *Arrows* in Fig. 7A indicate the 'Holocene high energy window' at around 5200 yBP.

waves break farther from the shore. At 3500 yBP, the western Tonaki reef flat accreted to approximately half way across the present-day reef flat (Fig. 7B). The sea level fall and reef maturation with development of wave resistant structures at the reef edge, provided shore protection and contributed to tombolo stability.

CONCLUSION

Sea level achieved a maximum ca. 0.9 to 1.3 m higher than present ca. 5200 yBP in Tonaki Island, the central Ryukyus. This Holocene maximum level extended until around 3650 yBP, with a relatively sharp fall taking place at that time.

Early development of the reef in Holocene times was influenced by substrate topography that produced an initial zonation contrasting the outer windward margin, and the inner sheltered reef. Spur and groove systems were initiated with major reef accretion occurring by growth of the reef edge spurs. As inner grooves have become isolated from the sea, they have been infilled during storms by rounded coral clasts. The deposition of subaerial deposits of the tombolo of Tonaki Island is linked both to the accretion of the reef flat seaward, and to a fall in sea level about 3650 yBP.

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